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Forests of the sea: Predictive habitat modelling to assess the abundance of canopy forming kelp forests on temperate reefs

Mary Young [a,*], Daniel Ierodiaconou [a], Tim Womersley [b,c]

[a] Centre for Integrative Ecology, School of Life and Environmental Sciences, Deakin University, Warrnambool VIC, Australia
[b] DHI Water and Environment Pty Ltd., Perth, WA, Australia
[c] Water Technology, Perth, WA, Australia

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ABSTRACT

Large brown seaweeds (kelps) form forests in temperate and boreal marine systems that serve as foundations to the structure and dynamics of communities. Mapping the distributions of these species is important to understanding the ecology of coastal environments, managing marine ecosystems (e.g., spatial planning), predicting consequences of climate change and the potential for carbon production. We demonstrate how combining seafloor mapping technologies (LiDAR and multibeam bathymetry) and models of wave energy to map the distribution and relative abundance of seaweed forests of *Ecklonia radiata* can provide complete coverage over hundreds of square kilometers. Using generalized linear mixed models (GLMMs), we associated observations of *E. radiata* abundance from video transects with environmental variables. These relationships were then used to predict the distribution of *E. radiata* across our 756.1 km^2 study area off the coast of Victoria, Australia. A reserved dataset was used to test the accuracy of these predictions. We found that the abundance distribution of *E. radiata* is strongly associated with depth, presence of rocky reef, curvature of the reef topography, and wave exposure. In addition, the GLMM methodology allowed us to adequately account for spatial autocorrelation in our sampling methods. The predictive distribution map created from the best GLMM predicted the abundance of *E. radiata* with an accuracy of 72%. The combination of LiDAR and multibeam bathymetry allowed us to model and predict *E. radiata* abundance distribution across its entire depth range for this study area. Using methods like those presented in this study, we can map the distribution of macroalgae species, which will give insight into ecological communities, biodiversity distribution, carbon uptake, and potential sequestration.

1. Introduction

Descriptions of relationships between species and their physical environment have long been a part of human's study of nature. In the terrestrial realm, our ability to remotely monitor the state of biodiversity across landscapes has been imperative for developing effective adaptation strategies to mitigate further loss of biological diversity and other impacts of global environmental change (Rodriguez, Brotons, Bustamante, & Seoane, 2007; Thuiller, 2007). Originally dominated by qualitative descriptions, the field of ecology has moved to quantitative techniques for describing species-habitat relationships (Elith & Leathwick, 2009). Species distribution models (SDMs), which were developed in terrestrial systems, are now a common method of associating species or communities with their environment across many systems and allow extrapolation of spatially restricted observations throughout entire landscapes (Guisan & Zimmermann, 2000; Stauffer, 2002; Guisan & Thuiller, 2005; Guisan, Graham, Elith, Huettmann, & the NCEAS Species Distribution Modelling Group, 2007; Richards, Carstens, & Lacey Knowles, 2007; Marmion, Parviainen, Luoto, Heikkinen, & Thuiller, 2008; Schröder, 2008; Elith & Leathwick, 2009; Ross & Howell, 2012). SDMs have many applications especially as spatial management is becoming more prevalent in both terrestrial and marine systems. However, obtaining similar information in the marine realm has been problematic with the majority of our ocean still a mystery. In the marine environment, where it is difficult to intensively sample over large areas, SDMs are extremely useful for understanding species distributions across landscapes (Elith & Leathwick, 2009). Mapping out the spatial distributions of marine species can help with coastal management (Margules & Pressey, 2000; Jordan, Lawler, & Halley, 2005; Ross & Howell, 2012; Rees, Jordan, Price, Coleman, & Davis, 2014), inform ecological studies (Duarte, 1999), and quantify biodiversity in marine systems (Gray, 2001; Fernandes et al., 2005; Rees et al., 2014).

Development and application of SDMs in the marine environment has increased with recent advances in acoustic technology (e.g. multibeam sonars) to collect high resolution data on seafloor structure (Hughes Clarke, Mayer, & Wells, 1996; Anderson, Van Holliday, Kloser, Reid, & Simard, 2008; Cogan, Todd, Lawton, & Noji, 2009). Unfortunately, some of the most ecologically and economically important

* Corresponding author.
E-mail address: mary.young@deakin.edu.au (M. Young).

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ecosystems and those at most risk are often within the shallow, nearshore environment (Carr and Reed, 2015) cannot be economically mapped using traditional, vessel-based acoustic methods due to reduction in data collection efficiency in shallower depths and navigation hazards (Irish & Lillycrop, 1999). Therefore, there is often a data gap between the shore and the shallowest depth at which the seafloor can be mapped using multibeam (Zavalas, Ierodiaconou, Ryan, Rattray, & Monk, 2014). The use of bathymetric LiDAR (light detection and ranging) is one method used to fill in bathymetry of the nearshore environment (Irish & Lillycrop, 1999; MacDonald, 2005; Wedding, Friedlander, McGranaghan, Yost, & Monaco, 2008). Integrating bathymetric LiDAR and multibeam bathymetry datasets provides an opportunity to generate seamless high resolution mosaics of seafloor structure in coastal zone studies as have been applied to mapping elevation data on coral reefs (Costa, Battista & Pittman, 2009; Leon, Phinn, Hamylton, & Saunders, 2013), hydrographic surveys (Pastol, 2011) and assessment of granitic coast evolution (Kennedy, Ierodiaconou, & Schimel, 2014). This information can be used to generate morphometric layers characterizing variation in seabed and combined with "ground-truth" observations to help develop habitat maps. To date, habitat maps have been relatively rare in shallow, nearshore marine environments in temperate latitudes (Galparsoro et al., 2012). Recent studies have shown multibeam and LiDAR bathymetry data collection and quality are similar for identifying bathymetric features (Costa et al., 2009) but the integration of the two datasets results in a lower resolution final product, if a single resolution is required for analyses, than could be produced with multibeam data alone. Also, most of these studies are done in tropical regions and those that were completed in temperate regions resulted in mosaics with many gaps due to increased turbidity, swell action, etcetera (Intelmann, 2006).

Although the collection of LiDAR data doesn't suffer the same limitations from ship-based navigation hazards and inefficiency in shallow waters, turbidity and surf breaks can often inhibit the collection of full-coverage LiDAR data (Intelmann, 2006). To overcome these inhibitions, it is important to plan LiDAR surveys around ideal conditions or the actual coverage will be much less than the potential coverage based on depth, especially in temperate regions where water clarity can vary substantially. Once collected, the merging of LiDAR and multibeam data can be problematic since they are often collected by different organizations for different purposes and the vertical reference frame may vary (Intelmann, 2006). Once these issues are accounted for, integrating multibeam and LiDAR data can be useful for creating species-specific habitat maps. The combination of multibeam and LiDAR data for creating seamless habitat maps, however, is rare. Most studies use one method and neglect to create habitat maps across the entire depth distribution of nearshore marine species.

The ability to acquire data across all depths in marine nearshore environments is particularly useful in characterizing distributions of photosynthetic organisms that become light limited in deeper waters, such as macroalgae communities. Using either of these techniques in isolation may fail to encompass a species' depth distribution and ecological range. Similar to forests in the terrestrial environment, large brown seaweeds (kelps) form forests in temperate and boreal marine systems that serve as foundations to the structure and dynamics of communities (Miller, Mann, & Scaratt, 1971; Dayton, 1975; Graham, Vásquez, & Buschmann, 2007; Carr & Reed, 2015). These algal assemblages often contain a dominant, canopy-forming kelp that has a large influence on the rest of the assemblage (Dayton et al., 1984; Melville & Connell, 2001; Toohey et al., 2004). The biogenic habitat created by these foundational species supports nearshore biodiversity (Coleman et al., 2011a). *Ecklonia radiata* is a dominant species of kelp that is common from 2 to 25 m in Australia's temperate subtidal from Coff's Harbour in New South Wales to Kalbarri in Western Australia (Womersley, 1981). *E. radiata* is a very productive laminarian that occurs in high biomass patches and reaches heights around 2 m from the substrate surface (Navaczek, 1984; Larkum, 1986). It provides habitat for species, contributes to detrital food webs and negatively influences the abundance and species richness of the algae inhabiting its understory (Edmonds & Francesconi, 1981; Robertson & Lucas, 1983; Kennelly, 1989; Kendrick, Harvey, Wernberg, Harman, & Goldberg, 2004). Understanding the broad scale distribution and abundance of *E. radiata* can provide insight into the community dynamics of temperate reefs.

In this study, we use a combination of multibeam and LiDAR bathymetry data along with models of wave exposure to associate spatially-explicit observations of *E. radiata* abundance with depth, the structure of the seafloor and the wave environment. The combination of the two bathymetric datasets allows us to model the distribution of *E. radiata* across its entire depth range. By associating the distribution of *E. radiata* with broad scale environmental variables we can better understand the factors in the environment correlated with its distribution and extrapolate its distribution over broader environmental scales.

2. Methods

2.1. Study site

This study was conducted on the Otway coast of Victoria, southeastern Australia. The site extends approximately 130 km from east to west around Cape Otway, a prominent feature of western Victoria (Fig. 1). Reef types are typically bedded sandstones with numerous crevices, parallel beds and spectacular fold structures. Much of the reef structure exposed west of Cape Otway is attributable to the intense wave energy, which prevails from the southwest, sweeping sediment off the shallow shelf. The proportion of offshore reef is substantially less east of Cape Otway, due to the south-easterly aspect of this stretch of coast affording more protection from southern ocean swells. Large sandy embayments characterize the site east of the cape, with topographically complex rocky reef systems extending offshore from major headlands, which typically plunge directly to bare sands in deeper water. Areas of shallow reef (generally <30 m) were populated by diverse assemblages of macroalgae, which are characterized by the canopy forming kelps dominated by *E. radiata*, while deeper reefs were populated by diverse communities of sponges and other sessile invertebrates (Ierodiaconou, Rattray, Monk, Laurenson, & Versace, 2011).

The wave climate at the site is typical of the continental margin of southern Australia, largely dominated by swell waves propagating from low pressure systems moving from west to east in the Southern Ocean (Hemer, Simmonds, & Keay, 2008). The majority of Australia's southern shelf is subject to persistent high energy swells of above 3.5 m 30–50% of the time (Porter-Smith et al., 2004) and annual return significant wave heights of up to 8.7 m (Harris & Hughes, 2012). The orientation of Cape Otway to prevailing southwesterly swells causes a gradient of wave energy across the site.

2.2. E. radiata biological sampling

Observational data were collected using acoustically located towed video from a range of habitat mapping studies conducted from 2006 to 2009 (Ierodiaconou et al., 2011; Rattray, Ierodiaconou, Monk, Versace, & Laurenson, 2013; Rattray, Ierodiaconou, Monk, Laurenson, & Kennedy, 2014; Blake, Ball, & Coots, 2012). The multibeam and LiDAR bathymetry products for the site were used to design sampling in order to capture the range of depths and topographic and textural diversity across the region. In total, 88 transects perpendicular to the coast covering 225 linear kilometers were collected during summer across all years. Summer is believed to be the season of highest *E. radiata* cover. The system was towed at an average speed of 1–1.5 knots and at approximately 1–2 m above the seabed with field of view at a 45° angle to the seabed. An ultra-short base line transponder attached to the video unit allowed 3-dimensional positioning of the video unit relative to the vessel's dGPS antenna resulting in a total propagated error of ±3.6 m for video seafloor position (Rattray et al., 2014). Video frames